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DRILLING OPTIMIZATION USING MINIMUM ENERGY CONCEPT

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ABSTRACT

Sensitivity of the drilling economy to the daily oil price and a high amount of money expended in a short time to drill a well makes drilling optimization more important than optimization of any other operation related to petroleum engineering. A small improvement in drilling tool or a right decision by operator can save a high amount of money in drilling and a small misstep could spell disaster for drilling contractor, especially for small companies. In this work the simple yet powerful principle of minimum energy concept was used for analyzing the efficiency of drilling operation. In this method, although more emphasis has been placed on the mechanical and hydraulic energy, all of the expended energy in drilling operation can be integrated over time. In fact, this concept not only emphasis on considering expended energy as a comparative tool instead of horsepower, but also it considers integration of consumed energy over the time to apply the important rule of the time in drilling economy. For any drilled depth, this integral will have a value, which represents the efficiency of drilling. Drilling process is said to be efficient if the value of the integral is minimum in comparison with the other drilling operations. This analysis helps us to point out where it is possible to save on drilling cost. This method also allows the operator to closely monitor his daily expenditure of energy and the time over which this energy is expended in order to control the economy of the drilling operation. Minimizing the value of integral optimizes the whole drilling operation and not only the energy consumed. This is hidden in term "t" which appears in the integral after integration of energy over the time; because all power is spent in this time and minimizing this could save in all operations that are done within this time. Three application of this analysis will be introduced in this work. These three applications are: application in comparative analysis and benchmarking, application in bit selection, and application in dull bit evaluation.

KEYWORDS: Drilling, Optimization, Minimum Energy Concept, Drilling Cost

INTRODUCTION

The goal is to find a simple, reliable, and quick method that can be used to quantify a given drilling practice. Discussing total rig horsepower, as introduced by Warren1 as energy consumption per unit time in the proposed equation cannot be a "rig friendly" tool because the time has been taken out of the equation. Therefore, trying to minimize the power in this manner cannot be even representative of the optimized energy consumption.

The specific energy concept cannot be the suitable function that represents the expenditure of the energy of the whole system as well. In this work we try to find a concept that can be used as a tool that represent the whole drilling process or any other system. In fact, it has been tried to find a function that can be used to minimize the expenditure of the energy during the drilling process from rig up until rig down.

Reviewing proposed bit selection methods has shown that a function that considers both formation properties and drilling economy to select the proper bit has not been developed. Specific Energy methods that consider formation drill ability for applied energy, either has technical problem or requires special skills and experiences. In this work we have tried to introduce a method that does not have these problems.

THEORY

Horsepower, or simply power, is defined as "Force multiplied by Velocity":

$$P = F \times V \tag{1}$$

For any system like drilling rig, total energy expended can be calculated by multiplying a constant horsepower by time and if horsepower is not constant, it can be calculated by integrating horsepower over the time:

$$E = \bar{P} \times t \text{ or } E = \int_{t_o}^{t_1} P\,dt \tag{2}$$

"Lagrangian" Energy is the difference between kinetic energy and potential energy, and it can be written as:

$$E_l = K_E - P_E \tag{3}$$

From the equation (3), we can see that (1) E_l is a function of Displacement (D), Velocity (V), and time (t), and (2) when the difference between the above two parts of the Lagrangian function in time t_1 and t_2 is ZERO, then the function has an "Extreme" or "Extrimum" value. Taking derivative of E_l with respect to the variables of displacement, velocity, and the time, we obtain:

$$dE_l = \sum_{j=1}^{n} \left[\left(\partial E_l / \partial D_j \right) dD_j + \left(\partial E_l / \partial V_j \right) dV_j \right] + \left(\partial E_l / \partial t \right) dt \tag{4}$$

Replacing the derivatives of energy with respect to velocity and displacement with Momentum and Displacement, we will have:

$$dE_l = \sum_{j=1}^{n} \left[\left(M' - F_j \right) dD_j + F dV_j \right] + \left(\partial E_l / \partial t \right) dt \tag{5}$$

By changing the dependency of the Equation (5) to Mj instead of Vj, we will end up with "Hamiltonian" functions. To arrive at the Hamiltonian Function, we need to express Equation (3) in the following form.

$$P_E = K_E - E_l \tag{6}$$

$$K_E = M_j V_j \tag{7}$$

Taking the derivative of Equation (6) we have

$$d\left(K_E - E_l\right) = \sum_{j=1}^{n} \left(M_j dV_j + V_j dM_j \right) - dE_l \tag{8}$$

Substitution of equation 5 in 10 will yield:

$$d\left(K_E - E_l\right) = \sum_{j=2}^{n}\left[\left(F_j - M'\right)dD_j + V_j dM_j\right] - \left(\partial E_l / \partial t\right) \tag{9}$$

As we can see, the Hamiltonian function depends on the variables D, M, and t; therefore, we may write the Hamiltonian function and its derivative in the following form:

$$K_E - E_l = H_l = \sum_{j=1}^{n} M_j V_j - E_j \tag{10}$$

H_l : Hamiltonian function, energy units

$$\partial H_l / \partial D_j = F_j - dM_j / dt \tag{11}$$

$$\partial H_l / \partial M_j = V_j \tag{12}$$

$$\partial H_l = -\partial E_l / \partial t \tag{13}$$

To proceed toward our goal, we divide both sides of the Equation (10) by dt.

$$dH_l / dt =$$

$$= \sum_{j=1}^{n}\left[\left(\partial Hl / \partial D_j\right)dD_j / dt + \left(\partial H_l / \partial M_j\right)dM_j / dt\right] + \partial H_l / dt$$

$$= \sum_{j=1}^{n} F_j V_j + \partial H_l / \partial t \tag{14}$$

This is the definition of power in terms of Hamiltonian mechanics, which that we mentioned in Equation (1).

$$dH_l / dt = \text{Power} = \sum_{j=1}^{n} F_j V_j \tag{15}$$

Effort has been formed to find a function that limits the problems of previously developed methods led us to the concept of Energy multiplied by Time; $E \times t$. Hayatdavoudi2 developed this concept and field practice in his previous work. This can be the function that satisfies the objective of the work. In this work the focus will be on modifying his work and then, we will validate it by applying the theory to real data from the field for 70 wells. For the sake of simplicity, this concept always has been shown as $E \times t$, but actually, it is not $E \times t$; instead it is the integration of energy consumed (E) over time (t). In a very small period of time, this function will be $E \times t$. This task requires us to integrate Equation (15) for a system like a drilling rig in the following way:

$$H = \int_{H1}^{H2} dH_l = \int_{t_1}^{t_2}\left(F_j V_j\right)dt = \int_{t_1}^{t_2} P dt$$
$$= P\left(t_2 - t_1\right) = E_{\text{system}\,(t_2 - t_1)} \tag{16}$$

If Power, P is not constant, we write Equation (16) as:

$$H = \sum_{j=1}^{n} P_j \Delta t_j \tag{17}$$

The integral form of Equation (17), Et can be written as:

$$Et = \int_{t_1}^{t_2} \Delta H dt = \int_{t_1}^{t_2} Ptdt = P\frac{t^2}{2} \tag{18}$$

And if Power, P is not constant, we write Equation (18) as:

$$Et = \sum_{j=1}^{n} P_j \Delta t_j^2 \tag{19}$$

Furthermore, we can write Equation (19) by its equivalent form:

$$Et = E_{system}\frac{\Delta t}{2} = P_{system}\frac{\Delta t^2}{2} \tag{20}$$

This value must be corrected or normalized for the wellbore diameter in order to make the Equation (20) simple and applicable for fieldwork for different hole diameters. We use specific energy multiplied by the length of the drilled interval instead of energy to normalize the equation for wellbore diameter. And the author's new definition of Et is:

$$Et = SE_{system} L \frac{\Delta t}{2} \tag{21}$$

Evaluation of real world examples using different specific energy methods showed that the results from these methods do not match. Now we discuss the application of this concept and prove that Et can be the desired function for use in drilling optimization.

In some specific energy models 3, 4, 5, 6, 7 the researchers have taken only the mechanical horsepower into account, but since Et represents the whole system expenditure of energy, it includes hydraulic horsepower, as well. In this manner, therefore, we use the total rig horsepower, which is mainly the summation of mechanical and hydraulic energy. We use this extra term in our model because it is an inseparable part of all mechanical and hydraulic energies consumed by the system, not because of its effect on the rate of penetration. Therefore, for applied horsepower we write:

$$HP = W.R + T.RPM + P.Q \tag{22}$$

Or in horsepower units:

$$HP = W.R/(33000) + T.RPM/(33000) + P.Q/1714 \tag{23}$$

Substituting Equation (23) to Equation (21) and normalizing to hole diameter or area the author obtains:

$$E = \left[\frac{WR}{550} + \frac{T.RPM.d}{175} + \frac{PQ}{28.5}\right].t \text{ and } SE = \frac{1}{45}\left[\frac{W}{38.4d^2} + \frac{T.RPM}{6.Rd} + \frac{PQ}{Rd^2}\right] \tag{24.a}$$

$$Et = \frac{4L}{3}\left[\frac{W}{38.4d^2} + \frac{T.RPM}{6.Rd} + \frac{PQ}{Rd^2}\right].t \tag{24.b}$$

And for real time data we have:

$$Et_j = \frac{4}{3}L_j\left[\frac{W_j}{38.4d^2} + \frac{T_j.RPM_j}{6.R_j d} + \frac{P_j Q_j}{Rd^2}\right].\Delta t_j \tag{25.a}$$

If integration is calculated for a continuous energy function, the value of Et function for any point can be calculated from Equation (25.b)

$$Et_j = \frac{(E_j + E_{j-1})L}{2RA} + Et_{j-1} \tag{25.b}$$

Et analysis method can be used with real time data as well as the offset bit records and for drilling performance analysis.

We can plot the value of Et against the depth drilled. For any drilled depth the value of Equation (25.b) will be a number that represents the efficiency of the drilling operation. In this case, t in these Equations will be the time at which we reach a specific depth point. We can, therefore, generate an Et log for the entire well or for each bit run depending on the application, in offset bit record analysis or in real time during drilling.

Bit records are known to be a proper source of information for analyzing performance of drilled wells and establishing a benchmark drilling operation or bit run. All of the existing parameters in Equation (25.a) can be found in bit records. For the purpose of monitoring drilling operation, the ROP log, (drill-time log), is also needed because the average ROP is not adequate for these applications, and we need to calculate the value of Equation (25.b) for a number of points and plot them versus depth. In oilfield application, the real time data is used in this analysis instead of bit records.

Often, bit torque is not recorded in bit records, but it can be estimated using the other information that exists in the bit record. For our analysis, we have selected Warren's torque model, Equation (26). The model can be applied safely to the geographical and geological focus of our research. Warren's torque model is:

$$T = \left[3.79 + 19.17\sqrt{R/(Nd)}\right]Wd\left(\frac{1}{1 + 0.00021L}\right) \tag{26}$$

E.t is a universal concept and in physics it is called plank's constant. The concept of E.t was used in some researches in other areas but its importance and effectiveness has not been understood so far.

APPLICATION

Evaluation of Drilling Efficiency and Benchmarking

In the initial stages of well planning, it is the Equation (25) that we evaluate to prepare Authority For Expenditure, AFE. Equation (25) gives us a sound and easy means of monitoring, tracking, and constantly evaluating our rig energy budget in order to take the necessary steps toward optimizing rig operations at all times.

In any step of drilling operation we want to minimize the fundamental integral, Equation (19). And if there are some offset wells drilled in the area that we are drilling, we try to bid the established benchmark bit record. Whenever the

value of the integral is too far to the right of the benchmark well for the same depth, it shows that the drilling efficiency is decreasing. In situations like that, the parameters involved in the Equation (25) must be changed in order to improve the drilling efficiency. Figure 1 shows how the benchmark operation falls on the left side. It can be understood from this figure that benchmarking for different drilling phases would be better than considering the whole operation for one well.

Bit Selection

Since equation (22) is a better tool than the specific energy to analyze and evaluate the drilling operation, we can use it in selecting a proper bit. Et must be plotted for all the wells drilled in the area of interest. After establishing the benchmark well, the same bit or closest one to it can be selected to be used in the well that is being planned. As in the case of specific energy, the problem with this method is that the best bit may not have been run in the area. In this case we should rely on the judgment and recommendations of the bit manufacturers.

As soon as we establish a benchmark bit run for each interval, we can use the bit that was run for the benchmark well to drill the same interval of the well that will be drilled. A plot similar to Figure 1 can be prepared and used for this purpose. Usually a large number of data must be used for bit selection, but for simplicity we used this example with only 4 wells. As we can see, well number 4 was the most efficient well drilled in the area. In this example 3 phases of drilling (surface, intermediate, and production) were drilled using only three bits in three runs. According to Figure 1, if we want to start at a depth of 2000 ft., we should select the bit used in well number 4 for this well in this depth interval. This bit drilled to a depth of 8000 ft., and its curve has the smallest slope until a total depth of 8,000 ft. has been reached. This means that, for a start, at any depth above 8,000 ft. this bit is the best option for drilling this interval. For the same reason, for depths from 8,000 ft., to 11,000 ft., still the same bit should be used. Below 11,000 ft., we have only two options and among these two, the bit used for well number 3 is better than the one for well number 1.

Dull Bit Evaluation

In order to estimate the bit dull condition from drilling efficiency data, there must be a good understanding of how the incremental bits wear affects different drilling conditions. In most rigs drilling rate, ROP, data is normally used to decide when to pull the bit out. There are two losses with this decision making process. The first is that the reason for low efficiency may not be the bit condition. The second reason is that the rate of penetration, ROP, and the specific energy plots (logs) usually show several peaks and deciding on which peak is really caused by the dulled bit is very difficult. Woughman et al.7 used mechanical specific energy to see when it is time to pull the worn PDC bits. Their method still has the same problems, and the mechanical specific energy plot has no advantage over the ROP (drill-time) log.

Et can be a better tool for monitoring dull condition. Because the cumulative energy is used in calculating Et, when plotting Et against measured depth, the curve will show an ever-increasing trend. Assuming that the bit is always sharp and the formation is always homogeneous, this curve must have a constant slope. For normal drilling operations in which the bit dulls as drilling proceeds and the formation properties always change, the slope of the curve in a chosen scale will also have an ever-increasing trend. The slope increases until it becomes close to 90 degrees. This situation means that for the applied energy we have a small increment in drilled depth.

The best means to define slope of a curve is to use the concept of derivation. According to Leibniz' rule, derivative of a function $y = f(x)$ with respect to x, is obtained by simply dividing increase in y, (Δy) by the increment of x, (Δx) that caused this variation in y. The important point is that the scale of the (x,y) graph must be used in the equation.

Based on this discussion, the author has discovered that, actually, the slope of the Et enhances the understanding of when to pull the bit. Since the slope is a tangent of an angle, it ranges between zero and infinity. However, if we express the slope in terms of Sine function (an odd function), it will range between zero and one. We define this new variable, which we call SEt. Therefore, the final equation that gives us a better understanding of dull bit condition is:

$$\text{SEt} = \text{Sin}\left[\text{Arc}\tan\left(\frac{\Delta \text{Et}}{\Delta \text{D}}\right)\right] \tag{29}$$

A bit is said to be worn at any depth when the Sine of the angle that a curve makes with its tangential line reaches ‘Unity, one’. When the Sin of the angle is one, it means zero penetration rate and zero efficiency. The point at which the drilling must be stopped depends on the cost per foot of the drilling. Therefore, we need to specify a limit for cost-per-foot value of Equation (29). If the cost-per-foot is high, SEt is closer to one than when the cost-per-foot is low.

As we can see in Figures 2 and 3, the Slope of the Et curve increases until the curve approaches horizontal asymptote, which is the indicative of very low efficiency. In Figure 4, the slope gradually increases up to 10,440 ft. At this depth, the slope increases rapidly and the curve approach horizontal asymptote. The operator continues to drill to make sure whether this is a hard streak or the bit is dull. After a few feet the slope decreases and keeps its normal trend. This proves that the low drilling rate at the depth of 10,440 ft. is because of a hard streak, or a change in the formation. A premature bit trip at this depth would result in pulling a “green” bit. This would be certainly a waste of time and money. We observe the same change of the slope again at 10,550 and 10,640 ft. The operator makes the same decision and he does not stop drilling, and again he is successful in his decision. Between 10,640 and 10,720 ft. there is a hard formation, which causes a high slope in the curve. After this formation change, again the curve keeps its normal trend and at 10,800 ft., again the slope increases and the curve approaches almost horizontal asymptote. At this point, the driller pulls the bit correctly.

In Figure 3, two rapid increases in slope can be seen at 11,025 and 11,070 ft. Because the bit was new, the driller knew that these two were most probably because of hard formations and he kept on drilling. After these two points, the driller drilled with a normally decreasing ROP to the depth of 11,358 ft. At this depth, the Et curve approaches the horizontal asymptote, and the bit must have been pulled out. The value of Sine of the slopes has been calculated for Figures 2 and 3 using equation 23. We have plotted the results versus depth. The results of such an analysis are shown in Figures 4 and 5. In addition to the discussion above we have made some modification to the Et methodology for new applications which they will be published in a separate paper.

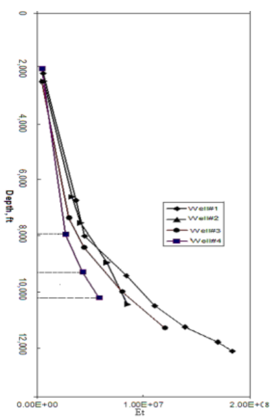

Figure 1: Using Et in Bit Selection and Benchmarking

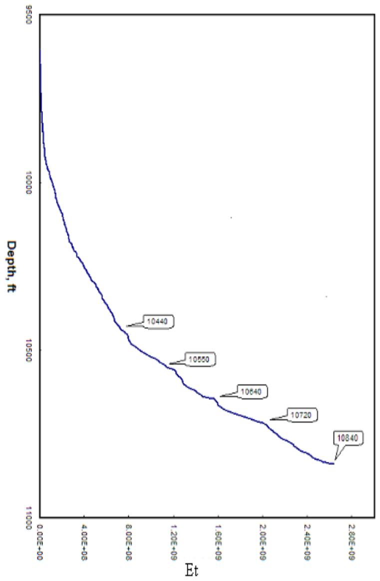

Figure 2: Application of Et for Dull Bit Evaluation

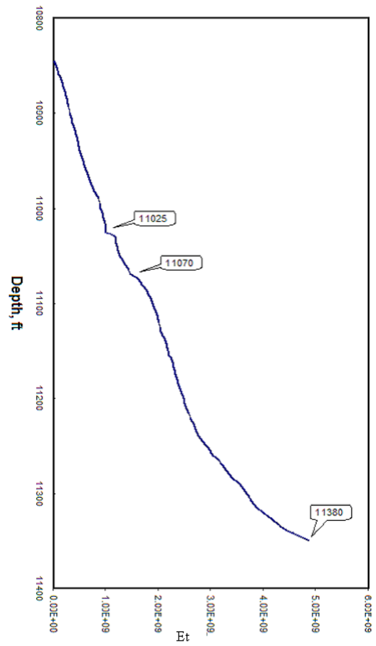

Figure 3: Application of Et for Dull Bit Evaluation

CONCLUSIONS

On the basis of our results, we conclude that:

In order to achieve a good drilling optimization program, all parameters involved in the drilling must be studied and analyzed together. Then, the best values for the drilling parameters must be selected or the most efficient drilling tools must be used for the existing drilling condition. We have shown that Et and field practice of the theory provides a tool for analyzing the drilling parameters.

Optimizing drilling cannot be achieved without minimizing the time. Obviously, the importance of the time cannot be ignored. We believe and proved in this research that by incorporating time in a specific energy model, and

integrating the energy over this time, the integral will give a better understanding of drilling conditions or any other operation in which the total expenditure and energy consumption is a part of the total expenditure of energy and time together.

By using the field data, we supported the idea that our proposed method of evaluating drilling efficiency is superior to the existing models such as Specific Energy models. The Et is the proper tool in evaluating drilling efficiency, selection of proper bit, and understanding when to pull the worn bit.

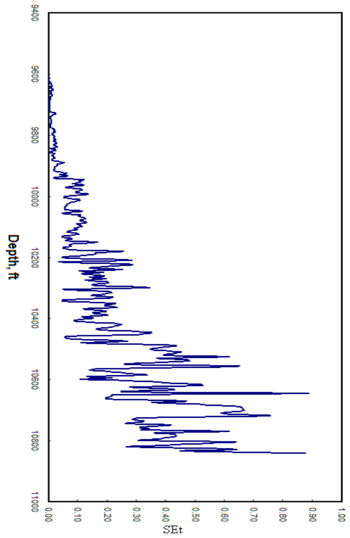

Figure 4: SEt versus Measured Depth for Bit Run in Figure 2 Set

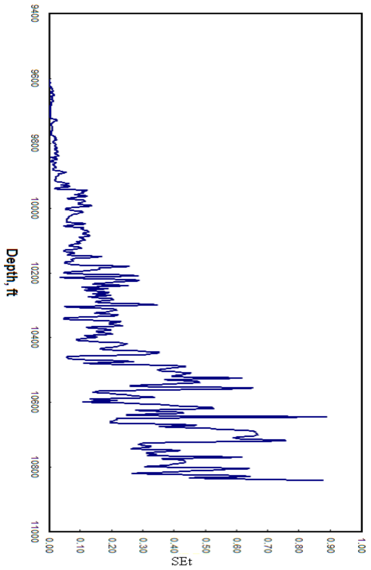

Figure 5: SEt Versus Measured Depth for Bit Run in Figure 2 SEt

Contractors can use the Et method of analysis to analyze the efficiency of the optimization program. Trying to minimize the value of Et will help the contractors use the optimize values for drilling parameters, and by using these values, a great amount of saving can be achieved.

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APPENDICES

NOMENCLATURE

P: Power, ft-lbs/sec

F: Force, lbs

V: Velocity, ft/min

W: Weight-on-bit, lbs

R: Rate of penetration, ft/min

T: Torque

RPM: Rotary speed

P: Pump pressure, psi

Q: Mud flow rate, gal/min

T: Torque, lb-ft.

R: Rate of penetration, ft/hrs

N: Rotary speed, RPM

d: Bit diameter, in.

W: weight-on-bit, 1000 lbs

t: time, hrs or min

L: Length of the drilled interval, ft.

A: Bit cross section area or the hole diameter

E_l : Lagrangian energy function

K_E : Kinetic energy, lb-ft.

P_E : Potential energy, lb-ft.

M' : Derivative of momentum with respect to time

F_j : Force acting on the jth component to displace or generate kinetic energy,

D_j : Displacement of the jth Component, ft.

V_j : Velocity of the jth component, ft/min

M_j : Momentum of the jth component

3.79 And 19.76: Constants from field data from South Louisiana